Partonic structure meets meson exchange: Exploring duality with transverse densities

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- Nucleon structure in QCD
  - Why parton picture
  - Transverse densities from elastic FFs

- Spectral analysis of transverse densities
  - Dispersion representation of densities
    Strikman, CW, PRC82 (2010) 042201
  - Large distances \( b \sim 2 \text{ fm} \): Chiral dynamics
  - Intermediate \( b \sim 1 \text{ fm} \): Vector mesons
    Miller, Strikman, CW, PRC84 (2011) 045205
  - Partonic interpretation

- Pion transverse charge density
  - Timelike FF from \( e^+e^- \) data:
    Pointlike \( q\bar{q} \) configurations
    Miller, Strikman, CW, PRD83 (2011) 013006

- Outlook: GPDs, new data

Express pion cloud, vector meson dominance in QCD!

Explore parton–hadron duality in \( t \)–channel kinematics!

Understand spatial structure of nucleon as relativistic system!
Nucleon structure: Parton picture

- QCD vacuum not empty
  - Strong non-perturbative gluon fields
    - Size $\ll 1$ fm. Lattice simulations, analytic models
  - $\bar{q}q$ pair condensate, $\pi$ as collective excitation
    - Chiral symmetry breaking; Order parameter, Goldstone boson

- Slow–moving nucleon $P \sim \mu_{\text{vac}}$
  - $\langle N | \hat{O} | N \rangle$ from correlation functions
  - No concept of particle content!
    - Cannot separate “constituents” from vacuum fluctuations

- Fast–moving nucleon $P \gg \mu_{\text{vac}}$
  - Closed system: Wave function, $x_i$, $k_{T_i}$
  - Longitudinal momentum densities: PDFs
  - Transverse spatial distributions: Form factors, GPDs
  - 2nd quantized operator definitions: Renormalization, scale dependence
  - Expresses low–energy dynamics!
    - “Point of view”
  - High–energy processes take snapshot
Nucleon structure: Transverse densities

- Current matrix element parametrized by invariant form factors
  \[ \langle N' | J_\mu | N \rangle \rightarrow F_1(t), F_2(t) \]  
  Dirac, Pauli

- Transverse densities \( t = -\Delta_T^2 \)  
  Soper 76, Miller 07
  \[ F_{1,2}(t) = \int d^2b \, e^{i\Delta_T b} \rho_{1,2}(b) \]  
  2D Fourier

  Transverse density of charge and magnetization \( b \) displacement from transverse C.M.

- Proper densities for relativistic systems
  Overlap of wave functions with same particle nr
  Breit frame distributions are not densities

  Spatial representation of relativistic system

- Reduction of quark distributions \( \text{GPDs} \)
  \[ \rho_1(b) = \sum_q e_q \int_0^1 dx \left[ q(x, b) - \bar{q}(x, b) \right] \]

  Relate elastic FFs to QCD quark/gluon structure
Nucleon structure: Empirical densities

- Empirical transverse densities from spacelike form factor data
  - Experimental and incompleteness errors estimated (Venkat, Arrington, Miller, Zhan 10)
  - Recent low– and high–$|t|$ data incorporated (MAMI: Vanderhaeghen, Walcher 10. JLab Hall A Riordan et al.)
  - Many interesting questions: Neutron, flavor structure, charge vs. magnetization

- Meson exchange picture
  - Current couples to nucleon via hadronic exchange mechanism
  - Relativity, causality: Analyticity, crossing invariance
  - Successful phenomenology: Vector dominance
    - Cf. $N\cdot N$ interaction parametrization Bonn potential
  - Relate to parton picture — quantitatively!
  - VMD expressed in QCD D.o.F
    - New insight into partonic structure
    - Parton–hadron duality in $t$–channel
Spectral analysis: Dispersion representation

- Dispersion representation of form factor

\[
F_1(t) = \int_0^{-}\frac{dt'}{4m^2_\pi} \frac{\Im F_1(t')}{t' - t - i0} \frac{\pi}{\pi}
\]

Spectral function \( \Im F_1(t') \) describes “process”
current \( \rightarrow \) hadronic states \( \rightarrow N\bar{N} \)

\( \Im F_1(t') \) from form factor fits and theory:
\( \chiPT \) near threshold, dispersion rels, pQCD \( t \to \infty \)

- Transverse density

\[
\rho(b) = \int_0^{-}\frac{dt}{4m^2_\pi} K_0(\sqrt{tb}) \Im F_1(t)
\]

\( K_0 \sim e^{-b\sqrt{t}} \) exponential suppression of large \( t \)

Distance \( b \) selects masses \( \sqrt{t} \sim 1/b \): “Filter”
Cf. Borel transformation in QCD sum rules. Strikman, CW 10

Peripheral \( \rho(b) \) \( \longleftrightarrow \) Low–mass hadronic states

- M

\[
M = \frac{2}{\pi} \rho
\]

\[ t = \sqrt{4M^2 - m^2} \]

- \( \pi \pi, \rho, \rho', \ldots \) Isovector
- \( \omega, \phi, K\bar{K}, \ldots \) Isoscalar

Im \( F_1(t) \) = 

\( N \) 

\( \bar{N} \) 

hadronic states 

\( b \) 

selects masses \( \sqrt{t} \sim 1/b \): “Filter”

Peripheral \( \rho(b) \) \( \longleftrightarrow \) Low–mass hadronic states
Spectral analysis: Isovector charge density

- Isovector spectral function

Near-threshold $\pi\pi$ from chiral dynamics
Universal, model-independent. Subthreshold singularity from $N$ pole. $\chi$EFT: Becher, Leutwyler 99; Kubis, Meissner 00; Kaiser 03

$\rho$ region from dispersion analysis
$\pi N$ and $\pi\pi$ phase shifts. Höhler 76; Belushkin et al. 05

High-mass continuum from form factor fits
Belushkin, Hammer, Meissner 07. Update Lorenz et al. 12

- Spectral analysis of isovector density

Near-threshold $\pi\pi$ relevant only at $b > 2$ fm
Surprisingly large distances!
Peripheral density from $\chi$EFT. Strikman, CW 10; Granados, CW 13

Intermediate $b = 0.5 - 1.5$ fm dominated by $\rho$, only $\sim 10\%$ correction from higher states
"Vector dominance" quantified in partonic picture

Higher-mass states relevant only at $b < 0.3$ fm
Average out at larger distances
Spectral analysis: Isovector charge density

Radial charge density $2\pi b \rho^V(b)$
Area under curve gives total charge

Isovector transverse charge density at $b \sim 1$ fm is dual to $\rho$ meson exchange with 90% accuracy!
Spectral analysis: Isoscalar charge density

- **Isoscalar spectral function**
  
  $\omega$ exhausts strength below 1 GeV$^2$
  Non-resonant $3\pi$ negligible

  Large negative strength above 1 GeV$^2$,
  dynamical origin unclear
  $\phi NN$ coupling $\leftrightarrow s\bar{s}$ content of nucleon

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07

- **Spectral analysis of isoscalar density**
  Miller, Strikman, CW 11

  $\omega$ dominates at $b > 1.5$ fm
  Fit uncertainty in $\omega NN$ coupling $\pm 15\%$

  Large cancellations between $\omega$ and higher–mass states at $b = 0.5 - 1$ fm

- **Impact of future form factor data**

  Sensitivity to $\omega NN$ coupling broadly distributed at spacelike $|t| \lesssim 1$ GeV$^2$
  Does not require measurements at extremely small $|t|$
• Spectral analysis of neutron density

\[ \omega - \rho \] alone gives large positive density!

Substantially reduced by higher–mass states in isoscalar spectral function

Neutron form factor measurements can help to determine isoscalar spectral function

\[ \rightarrow \phi NN \] coupling, \( s\bar{s} \) in nucleon
Parton interpretation: Quark densities

- Transverse densities of $u$ and $d$ quarks
  Constructed from FF fits. Small $b$ from JLab Hall A Cates et al. 11
  \[ \rho_u(b) = \int_0^1 dx \left[ u(x, b) - \bar{u}(x, b) \right] \text{ etc.} \]

- Ratio $\rho_d/\rho_u$ for interpretation
  Large $b$: $\rho_d/\rho_u \to -1$
  Peripheral $\pi N$ configs in nucleon WF
  Equivalence of invariant and light-cone $\chi$PT: Strikman, CW 10
  Same configs govern chiral contributions to PDFs: Strikman, CW 09
  Many interesting theoretical issues!

Intermediate $b \sim 0.3 - 1$ fm: $\rho_d/\rho_u \sim 1/2$
Mean-field motion of valence quarks
Cf. Quark model, large-$N_c$ QCD

Small $b < 0.3$ fm: $\rho_d/\rho_u < 1/2$
Extreme $x \to 1$ configs where $u \gg d$
PDF fits, pQCD counting

- Model-independent insights into partonic structure!
Parton interpretation: Duality

Partonic structure  

Isovector  
- Peripheral $\pi N$  
- Mean-field  
- Mean-field + large-$x$

Hadronic exchange  
- Near-threshold $\pi\pi$  
- $\rho$  
- $\rho + \text{high-mass}$

Disks indicate “region of dominance” of the various configurations/exchanges

- Parton–hadron duality explored locally in transverse space
- Model-independent, quantitative statements
- Benchmarks for dynamical model calculations
Parton interpretation: Much more information

- Pauli FF

  Transverse distribution of spin–dependent current
  \[ \rho_2(b) = \sum_q e_q \int_0^1 dx \left[ e_q(x, b) - e_{\bar{q}}(x, b) \right] \]

  nucleon helicity–flip GPD

- Axial and pseudoscalar FFs

  Transverse distribution of axial and pseudoscalar charge
  \[ \rho_A(b) = \sum_q \int_0^1 dx \left[ \Delta q(x, b) + \Delta \bar{q}(x, b) \right] \]

  spin–dependent parton densities

  - Pseudoscalar FF has \( \pi \) pole: Longest–range component of nucleon structure

- Energy–momentum tensor FFs

  Transverse distribution of momentum and matter

  Second moments of GPDS \[ \int_0^1 dx \, x \left[ q(x, b) + \bar{q}(x, b) \right] \] etc.

  \( C \)–even exchange: \( \sigma \)

- \( x \)–dependent form factors: GPDs

  Unify concepts of parton density and elastic FFs

  Probed in high–\( Q^2 \), low–\( t \) exclusive processes:
  Deeply virtual Compton scattering \( N(e, e'\gamma)N' \), meson production \( N(e, e'M)N' \)

  HERMES, COMPASS, JLab. Extensive program planned with JLab 12 GeV and future EIC. Analysis challenging!
Pion: Transverse density from timelike data

- **Spacelike FF poorly known at** $|t| > 1 \text{GeV}^2$
  
  Electroproduction on nucleon, model-dependent. JLab Hall C 6/12 GeV

- **Timelike FF from** $e^+e^-$ annihilation
  
  $|F_\pi|^2$ from cross secn, phase from models/theory

  Resonance–based parametrization from fit to data
  
  Bruch, Khodjamirian, Kuhn 04. CLEO 05 results not included.

- **Transverse density from dispersion integral**
  
  Miller, Strikman, CW 10

  \[
  \rho_\pi(b) = \int_0^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{tb}) \text{Im } F_\pi(t)
  \]

  Fully calculable, precise, error estimates

  Singular charge density at center of pion
Pion: Parton interpretation

- Singular charge density at center due to point-like configurations in pion wave function.

  Configs of size $r \ll R_\pi$, mostly elementary $q\bar{q}$

Observable in other high-momentum transfer processes: $\gamma^* \gamma \rightarrow \pi^0$, $\pi + A \rightarrow 2$ jets, . . .

Universal property

Large-size configurations with $x \rightarrow 1$ at scales $Q^2 > 1 \text{ GeV}^2$ cannot account for empirical charge density at $b \rightarrow 0$

Miller, Strikman, CW 10

Detailed modeling with light-cone wave functions in progress

- 2D image of fast-moving pion

First accurate transverse image based on data!
Summary: Theory

• Transverse densities connect partonic structure with hadronic spectrum
  Fully quantitative, consistent with QCD
  New approach to quark–hadron duality in $t$–channel

• Dispersion integral for $\rho(b)$ samples spectral function at masses $\sqrt{t} \sim 1/b$
  Systematic study of exchange mechanisms
  Mathematical properties: Asymptotic behavior, error analysis, . . .

• Nucleon charge density at intermediate distances $b = 0.5 - 1.5$ fm
  governed by vector mesons
  Chiral component relevant only at $b > 2$ fm
  Origin of isoscalar strength beyond $\omega$ still unclear

• Pion charge density from timelike form factor data
  Precise 2D image with controlled accuracy
  Singular charge density at center attributed to pointlike $q\bar{q}$ configurations
Summary: Experiment

- Can the chiral component be studied experimentally?
  
  Effect on low-\(Q^2\) form factors? Lorenz et al. 12
  
  CLAS/PRIMEX 12 GeV measurement at \(10^{-4} - 10^{-2}\) GeV\(^2\) PR12-11-106 Gasparian et al.
  
  Test fundamental \(\chi\)PT predictions!
  
  Affects extrapolation to \(Q^2 \rightarrow 0\)

- Dispersion fits to form factors provide much more information than \(Q^2\)-dependent parametrizations
  
  Should be updated with expected JLab 12 GeV data!
  
  Analyticity essential for studying nucleon's periphery

- Neutron form factor data crucial for determining isoscalar spectral function
  
  Impact on \(s\bar{s}\) content of nucleon